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**REPORT M 028**

# CYCLIC FATIGUE ANALYSIS OF SILICONE GEL-FILLED MAMMARY IMPLANTS

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# CYCLIC FATIGUE ANALYSIS OF SILICONE GEL-FILLED MAMMARY IMPLANTS

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## 1.0 TITLE

CYCLIC FATIGUE ANALYSIS OF SILICONE GEL-FILLED MAMMARY IMPLANTS

## 2.0 ABSTRACT

Cyclic fatigue testing of gel mammary implants has been completed to fulfill the requirements of Guidance for Saline, Silicone Gel, and Alternative Breast Implants; Guidance for Industry and FDA for Premarket Approval application. Experiments were performed to determine the number of cycles for various maximum loads at which devices fail or rupture and the endurance load at which devices do not fail. Resultant data is used to calculate a safety factor for relevant clinical significance that incorporates consideration of typical in vivo loading. This report presents the results of cyclic fatigue testing.

Experimental conditions and samples were chosen in compliance with FDA guidance. Cyclic fatigue tests were performed with servohydraulic testers equipped with an in vitro parallel plate fixture operated in load control (20-100 lb maximum load including a 10 lb holding load). Devices tested included Smooth Round Moderate Profile Gel-Filled Mammary Implants (100 cc), Siltex Round Moderate Profile Gel-Filled Mammary Implants (100 cc) and Siltex Round High Profile Gel-Filled Mammary Implants (125 cc). Device models represent dry heat sterilized finished product. These samples were assembled with smooth shells representing minimal radial shell thickness [redacted] and minimum textured sheeting thickness [redacted] Load and position were monitored for each test.

Results indicate that Smooth and Siltex Round Moderate Profile and Siltex High Profile Gel-Filled Mammary Implants exhibited fatigue failure for a maximum load range of 30-100 lb with corresponding cycles-to-failure of $N \sim 10^4 - 10^6$. Typically a minimum of three maximum load level tests resulting in failure was conducted for each device. The endurance limit tests that did not result in failure at run out ($10^7$ cycles) exhibited maximum load of 20 lb and 30 lb for smooth and textured devices respectively. Failure modes were characterized by a small tear located in the radial region of the device. The safety factors calculated from in vivo and endurance limit loading for smooth and textured devices was $S_f = 5.4 - 8.2$ for the largest volume devices and $S_f = 43.5 - 65.2$ for the smallest volume devices.

## 3.0 INTRODUCTION

Mentor Corporation manufactures Silicone Gel-Filled Mammary Implants for breast reconstruction and augmentation. Included are Smooth and Siltex Round Moderate, Moderate Plus and High Profile Gel-Filled Mammary Implants. Devices are comprised of a polysiloxane elastomeric shell and gel filler. The shell is a highly crosslinked material manufactured with dimethyl [redacted] polysiloxane dispersions supplied by [redacted] Gel is a lightly crosslinked material manufactured with polydimethylsiloxane supplied by [redacted] All device models are fabricated with the same raw materials and manufacturing processes and only differ in the shell shape. Accordingly testing of Smooth and Siltex Round Moderate Profile Gel-Filled Mammary Implants and Siltex Round High Profile Gel-Filled Mammary Implants encompasses all model variations.

Mammary prostheses experience various modes of mechanical loading, impact, and fatigue during their service life. Stresses caused by normal everyday activities are a result of routine oscillatory movements like walking and jogging. These movements subject the shell of the prosthesis to a fatigue lifetime when repeatedly stressed or strained. This can be investigated by cyclic fatigue testing, in which a compressive force is repeatedly applied to an intact mammary prosthesis until the device ruptures. The number of cycles the device can endure prior to rupture is an indirect estimate of time the device can remain intact in the body. The resulting data, defining the cycles-to-failure behavior of a device, can be used for calculation of a safety factor.

FDA has requested fatigue testing as described in Guidance for Saline, Silicone Gel, and Alternative Breast Implants; Guidance for Industry and FDA.[1] The fatigue test description includes selection of appropriate experimental conditions and samples chosen to represent product and relevant data acquisition and reduction. A fixture comprised of parallel plates was designed and assembled to induce uniaxial stress in the annular or radial region of the implant. Selection of the appropriate devices for testing, as recommended by FDA guidance, included consideration of various models, volume or size and thinnest shell thickness identified form design criteria to represent the worst case for resistance to cyclic compression loading. The smallest size smooth round high temperature vulcanized (HTV) shells were chosen that have the thinnest thickness at the radial or annular region of the shell. Thickness for various shell regions including anterior, posterior and radial have been verified from Quality Control traceability shell thickness measurement records from production shell lots. As a result, Smooth Round Moderate Profile Gel-Filled Mammary Implants (100 cc, dry heat sterilized), Siltex Round Moderate Profile Gel-Filled Mammary Implants (100 cc, dry heat sterilized) and Siltex Round High Profile Gel-Filled Mammary Implants (125 cc, dry heat sterilized) were selected to represent all Silicone Gel-Filled

Mammary Implant products (i.e. devices with the smallest and largest projection). The above devices were assembled with smooth shells representing the thinnest thickness [redacted] Cyclic fatigue testing was performed to determine the maximum applied force dependent cycles-to-failure (AF/N curve) and endurance limit. A safety factor was calculated based upon the endurance limit maximum load and an estimation of in vivo loading during typical activity such as walking. In addition, monotonic compression testing was conducted to ensure that maximum load amplitude levels were chosen in the viscoelastic response range of the device. This report presents data that has been accumulated for Smooth and Siltex Round Moderate Profile Gel-Filled Mammary Implants and Siltex Round High Profile Gel-Filled Mammary Implants.

## 4.0 EXPERIMENTAL

A detailed description of the experimental procedure is listed in Appendix A Protocol (Section 1 Protocol M 028 and Section 2 Test Fixture). All sample identification and preparation information is compiled in Appendix B Sample Information (Section 1 Sample List and Section 2 Manufacturing Quality Control Data for Measurement of Shell Thickness at Assembly).

### 4.1 Monotonic Testing

Monotonic servohydraulic testing (Instron 8511) was performed to determine the linear viscoelastic response range of devices. Prostheses were weighed and assembled in the test fixture. The test fixture and chamber are designed for in vitro uniaxial stress condition. The fixture is comprised of a stainless steel plate, which supports the device. A stainless steel plate, attached to the actuator and crosshead, compresses the device. A Plexiglas chamber houses the parallel plates and device. An illustration of the fixture is shown in Figure 1. The chamber is mounted on a 1000 lb (1 kip) load cell attached to the servohydraulic test frame. Monotonic compression testing was conducted in load control at T= 23 ± 2 °C. The load range used was ~0-1000 lb with 0.25 lb/s load compression rate. Load, position and time were monitored during the test. Several replicate devices were tested for each model (n= 3). All experimental conditions, including a listing of experimental parameters concerning instrument control and data acquisition were recorded.

### 4.2 Cyclic Testing

Cyclic fatigue testing was conducted to determine cycles-to-failure behavior of devices. The servohydraulic testers (Instron 8511 and 8872) were operated in load control at 1 Hz frequency. The fixture described above for monotonic testing was also used for cyclic testing with the exception of the load cell replacement with 200 lb capacity. Prostheses were weighed and assembled in the test fixture. Prior to commencing cyclic fatigue, each device was placed in the fixture containing physiologic saline and allowed to equilibrate for four hours at 37 °C. Foam sheeting was used adjacent to the anterior and posterior region of the device to insulate elastomer from metal and inhibit abrasion induced failure. Upon commencement of each test, the command and feedback signals were monitored and the gain parameters optimized. Load, position and cycles-to-failure were monitored with the data station. All experimental conditions, including a listing of experimental parameters concerning instrument control and data acquisition were recorded. Several cyclic load amplitudes were investigated to failure at a frequency of 1 Hz: 20, 30, 40, 50, 70 and 90 lb. A minimum 10 lb static load was imposed for each load amplitude test to prevent movement of the device. The static and cyclic loads were combined to yield the maximum load levels utilized for fatigue testing. Typically a minimum of three devices was tested for each maximum load level. The failure mode, failure location and envelope thickness at the failure site were also recorded. In addition, the endurance limit, or maximum load level for which failure does not occur before $10^7$ cycles was determined. A maximum load of 20 lb for smooth devices and 30 lb for textured devices was used for determination of the endurance limit at a frequency of 5 Hz. The accelerated frequency was validated for a maximum load level resulting in failure at 1 Hz by comparison of cycles-to-failure.

## 5.0 RESULTS

Cyclic fatigue raw data is compiled in Appendix C Raw Data [Section 1 Siltex Round Moderate Profile Mammary Implants (HTV Smooth Shell Fabrication Thickness [redacted] Section 2 Smooth Round Moderate Profile Gel Mammary Implants (HTV Smooth Shell Fabrication Thickness [redacted] Section 3 Siltex Round High Profile Gel Mammary Implants (HTV Smooth Shell Fabrication Thickness [redacted] and Section 4 Monotonic Compression Testing of Gel Mammary Implants]. Cyclic testing includes a description of test conditions, load and position dependent cycles-to-failure plots and illustration of failure (tear length and shell thickness at failure location) for each device tested. Compression testing includes a description of test conditions, load and displacement dependent time plots and illustration of failure mode. A summary of raw data is compiled in Appendix D Results and Calculations [Section 1 Siltex Round Moderate Profile Mammary Implants (HTV Smooth Shell Fabrication Thickness [redacted] Section 2 Smooth Round Moderate Profile Gel Mammary Implants (HTV Smooth Shell Fabrication Thickness [redacted] Section 3 Siltex Round High Profile Gel Mammary Implants (HTV Smooth Shell Fabrication Thickness [redacted] and Section 4 Monotonic Compression Testing of Gel Mammary Implants]. Cyclic testing includes tables listing device weight, static load, cyclic load amplitude, maximum load, cycles-to-failure, failure description, AF/N plots and statistical calculations of mean, standard deviation and coefficient of variation. In addition, statistical comparison (F-test and t-test) of 1 Hz and 5 Hz data is presented. Compression testing includes tables listing device weight, ultimate load at failure, failure description, load dependent displacement plots and statistical calculation of mean, standard deviation and coefficient of variation.

A summary of results is listed in Tables I-IV and illustrated in Figures 2-6.

## 6.0 DISCUSSION

Monotonic servohydraulic testing of devices revealed elastic, yield and plastic behavior throughout the applied load range. The elastic response region was observed for applied force of 0-100 lb which defines the linear viscoelastic region for dynamic testing. Accordingly, the maximum load values chosen for cyclic testing (20-100 lb) are within the linear viscoelastic response region of the device as defined from monotonic compression testing (Appendix D Section 4).

Typical cyclic servohydraulic testing position and load dependent cycles-to-failure curves are shown in Figures 2 and 3. It should be noted that device response does not attain equilibrium prior to ~1000 cycles. This is attributable to the instrument test initiation envelope and device compliance. Accordingly, this establishes the minimun cycle criterion for acceptance of a failure measurement experiment ($N \geq 1000$). In addition, constant load control activation results in no observed change for imposed load amplitude for the duration of testing. In contrast, the cycle dependent position minimum exhibits decay indicative of device compliance changes as a result of fatigue. Typical failure was characterized by a macroscopic tear originating in the radius of the device. The maximum load and corresponding cycles-to-failure data are summarized in Tables I-III. The relative standard deviations associated with these measurements are typical of fatigue testing and emphasize the importance of increasing the number of replicates to obtain meaningful results. Maximum load and cycles-to-failure values are linearly regressed to construct the AF/N curves shown in Figures 4-6 (plot abscissa linear maximum load scale, plot ordinate log cycles-to-failure scale). Typically the AF/N curve can be extrapolated to the y-intercept at $10^7$ cycles and allows for estimation of the endurance limit load amplitude. In this manner the maximum load value can be approximated eliminating iterative determination which can be prohibitively time consuming.

Failure data used for the AF/N curve were measured with a frequency of 1 Hz. The maximum load measured for the endurance limit is also indicated in the graphs, although no failure was observed for this condition. Endurance limit data were measured at a frequency of 5 Hz. Validation of the accelerated frequency testing for smooth and textured moderate profile devices was achieved by comparison of cycles-to-failure data obtained with 40 lb and 80 lb maximum loads respectively measured at 1 Hz and 5 Hz. Statistical comparison indicated no significant difference (Appendix D Sections 1 and 2). Accordingly no further validation of accelerated frequency was performed for textured high profile devices.

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Smooth Round Moderate Profile Gel Mammary Implant test results are listed in Table I and illustrated in Figure 4. The AF/N curve was established using a maximum load range of 30-60 lb and corresponding cycles-to-failure of N~ $10^4$-$10^5$. A 25 lb load amplitude was utilized to obtain N= $10^6$ cycles however the device achieved an endurance limit (N= $10^7$) and was retained with load limit test results. Failures were typically characterized by a tear originating in the radius of the device with length [redacted] In some instances it appeared that the rupture propagated into the anterior and posterior regions of the device. Since the extrapolated AF/N curve y-intercept at $10^7$ cycles yielded an estimated maximum load of ~15 lb it was decided to measure the endurance limit iteratively. A maximum load of 20 lb was chosen for this purpose. It should be noted that instrument failure (actuator seal leakage) occurred during acquisition of this data resulting in device rupture with successively decreasing cycles-to-failure (Appendix D Section 2). Upon instrument repair endurance limit testing was resumed. Data acquired during failure was eliminated from this maximum load testing. In addition one replicate failed prematurely and upon examination showed a shell thickness below minimum manufacturing specification [redacted] and was also discounted. It should be noted that some shells utilized for fabrication of devices indicated a thickness of [redacted] (see Appendix B Section 2). Accordingly it is conceivable that some finished product for testing may have exhibited a radius thickness less than the minimum specification of [redacted] When a shell thickness at failure was measured below the minimum specification the result was discarded and the test was repeated. The minimum endurance limit maximum load was chosen for calculation of the corresponding safety factor (see below).

Siltex Round Moderate Profile Gel Mammary Implant test results are listed in Table II and illustrated in Figure 5. The AF/N curve was established using a maximum load of 40-100 lb and corresponding cycles-to-failure of N~ $10^4$-$10^6$. Failures were typically characterized by a tear originating in the radius of the device with length [redacted] In some instances it appeared that the rupture propagated into the anterior and posterior regions of the device. The extrapolated AF/N curve y-intercept at $10^7$ cycles yielded an estimated endurance limit load amplitude of ~40 lb. Accordingly endurance limit testing was conducted at 30 lb load amplitude.

Siltex Round High Profile Gel Mammary Implant test results are listed in Table III and illustrated in Figure 6. The AF/N curve was established using a maximum load range of 50-100 lb which yielded cycles-to-failure of N~ $10^5$. This behavior is not understood since a larger range of cycles-to-failure should have resulted from the selected load amplitudes. One possibility is the device shell thicknesses measured at failure location exhibited significant variability [redacted] see Appendix D Section 3). Failures were typically characterized by a tear originating in the radius of the device with length [redacted] In some instances it appeared that the rupture propagated into the anterior and posterior regions of the device. Accordingly it was necessary to determine the endurance limit with iterative selection of load amplitudes as described above. Endurance limit was achieved with 30 lb and 40 lb maximum loads. The minimum endurance limit maximum load was chosen for calculation of the corresponding safety factor (see below).

Cyclic fatigue is used for calculation of the safety factor ($S_f$). The fatigue endurance limit safety factor approach relies upon an estimation of in-service maximum load assuming values for in vivo nominal load arising from prosthesis mass. The safety factor is calculated from the quotient of estimated in-service loading during walking or jogging ($F_s$= 2M, M= implant mass) and experimentally determined fatigue endurance limit maximum load ($F_{en}$). $S_f$= $F_{en}/F_s$ (Smooth and Siltex Round Moderate Profile Gel Mammary Implant: $F_s$~0.46 lb for the smallest device 100 cc and $F_s$~3.67 lb for the largest device 800 cc, Siltex Round High Profile Gel Mammary Implant: $F_s$~0.57 lb for the smallest device 125 cc and $F_s$~3.67 lb for the largest device 800 cc).[2] This data is listed in Table IV. The safety factor for the smallest devices for all three models tested yielded a range of $S_f$= 43.5-65.2. The safety factors for the largest devices exhibited a range of $S_f$= 5.4-8.2. The safety factors representing the largest devices were calculated using the endurance limit data obtained from the smallest device testing. This assumes that the largest device has the same fatigue endurance limit as the smallest device, which has not been demonstrated in this study due to instrument fixture size constraints that preclude measurement of the largest devices. Resulting safety factors for all devices exceed the minimum value agreed upon with FDA of $S_f > 2$.

## 7.0 ACKNOWLEDGMENTS

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## 8.0 REFERENCES

[1] Guidance for Saline, Silicone Gel, and Alternative Breast Implants; Guidance for Industry and FDA, U.S. Department of Health and Human Services, Food and Drug Administration, Center for Devices and Radiologic Health, Plastic and Reconstructive Surgery Devices Branch, Division of General, Reconstructive, and Neurological Devices, Office of Evaluation, February 11, 2003.

[2] Allen, G.M., "Cyclic Fatigue Analysis of Silicone Gel-Filled Mammary Implants," Protocol M 028, Mentor Corporation, Santa Barbara, CA, April 4, 2002.

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Table 1 Cyclic Fatigue Results for Smooth Round Moderate Profile Gel-Filled Mammary Implants
Catalog Number: 350-7100 BC Lot Number: 252289
Volume: 100 cc Sterilization: Dry Heat

| Maximum Load (lb) | Frequency (Hz) | Replicates (n) | Statistics | Device Weight (g) | Cycles (N) | Failure Mode | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Thickness (in) | Location | Description |
| 60 | 1 | 3 | X[b] | 110.0 | 16372 | [redacted] | Radius | Tear |
| | | | s[c] | 0.4 | 7814 | [redacted] | | |
| | | | CV[d] | <0.01 | 0.48 | 0.03 | | |
| 40 | 1 | 3 | X | 110.0 | 228819 | [redacted] | Radius | Tear |
| | | | s | 0.4 | 179508 | [redacted] | | |
| | | | CV | <0.01 | 0.78 | 0.05 | | |
| 30[a] | 1 & 5 | 3 | X | 110 | >2850552 | [redacted] | Radius | Tear |
| | | | s | 0.25 | 2437798 | NA | | |
| | | | CV | 0.002 | 0.86 | NA | | |
| 20 | 5 | 4 | X | 110.2 | 9217878 | No Failure[f] | | |
| | | | s | 0.2 | 1813852 | | | |
| | | | CV | <0.01 | 0.20 | | | |

[a] Two Samples are still in progresss
[b] X Mean
[c] s Standard Deviation
[d] CV Coefficient of Variation
[e] NA Not Applicable
[f] One test replicate failed at $6.5 \times 10^6$ cycles.

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Table III Cyclic Fatigue Results for Siltex Round High Profile Gel-Filled Mammary Implants
Catalog Number: 354-4125 Lot Number: 252291
Volume: 125 cc Sterilization: Dry Heat

| Maximum Load (lb) | Frequency (Hz) | Replicates (n) | Statistics | Device Weight (g) | Cycles (N) | Failure Mode | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Thickness (in) | Location | Description |
| 100 | 1 | 3 | X[b] | 133.1 | 18208 | [redacted] | Radius | Tear |
| | | | s[c] | 0.2 | 11955 | [redacted] | | |
| | | | CV[d] | <0.01 | 0.66 | 0.08 | | |
| 80 | 1 | 3 | X | 133.3 | 64027 | [redacted] | Radius | Tear |
| | | | s | 0.2 | 24289 | [redacted] | | |
| | | | CV | <0.01 | 0.38 | 0.07 | | |
| 60 | 1 | 3 | X | 133.7 | 75167 | [redacted] | Radius | Tear |
| | | | s | 0.6 | 21770 | [redacted] | | |
| | | | CV | <0.01 | 0.29 | 0.05 | | |
| 50 | 1 | 1 | X | 133.0 | 62925 | [redacted] | Radius | Tear |
| | | | s | NA[e] | NA | NA | | |
| | | | CV | NA | NA | NA | | |
| 30 & 40 | 1 & 5 | 3 | X | 133.4 | 10352524 | No Failure | | |
| | | | s | 0.2 | 316288 | | | |
| | | | CV | <0.01 | 0.03 | | | |

[b] X Mean
[c] s Standard Deviation
[d] CV Coefficient of Variation
[e] NA Not Applicable

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Table IV Silicone Gel-Filled Mammary Implant Fatigue Safety Factors

| Description | Size (cc) | In-Service Load ($F_s$ lb) | Endurance Load ($F_{en}$ lb) | Safety Factor ($S_f$) |
|---|---|---|---|---|
| Smooth Round Moderate Profile Gel Implant | 100 | 0.46 | 20 | 43.5 |
| | 800 | 3.67 | 20 | 5.4 |
| Siltex Round Moderate Profile Gel Implant | 100 | 0.46 | 30 | 65.2 |
| | 800 | 3.67 | 30 | 8.2 |
| Siltex Round High Profile Gel Implant | 125 | 0.57 | 30 | 52.6 |
| | 800 | 3.67 | 30 | 8.2 |

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Figure 1 Parallel Platen Servohydraulic Cyclic Fatigue Test Fixture

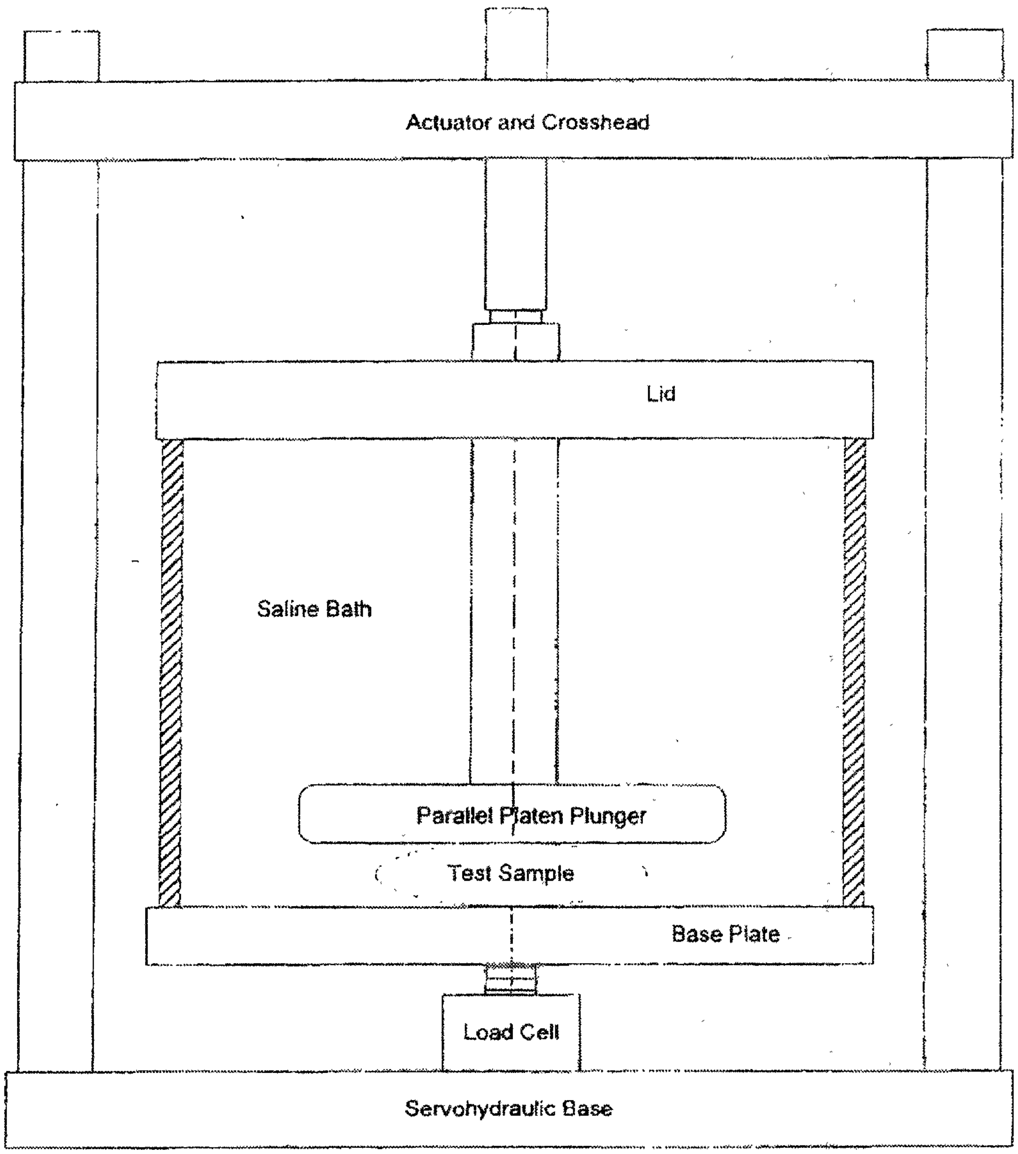

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Figure 2 Cyclic Fatigue Position Dependent Cycles

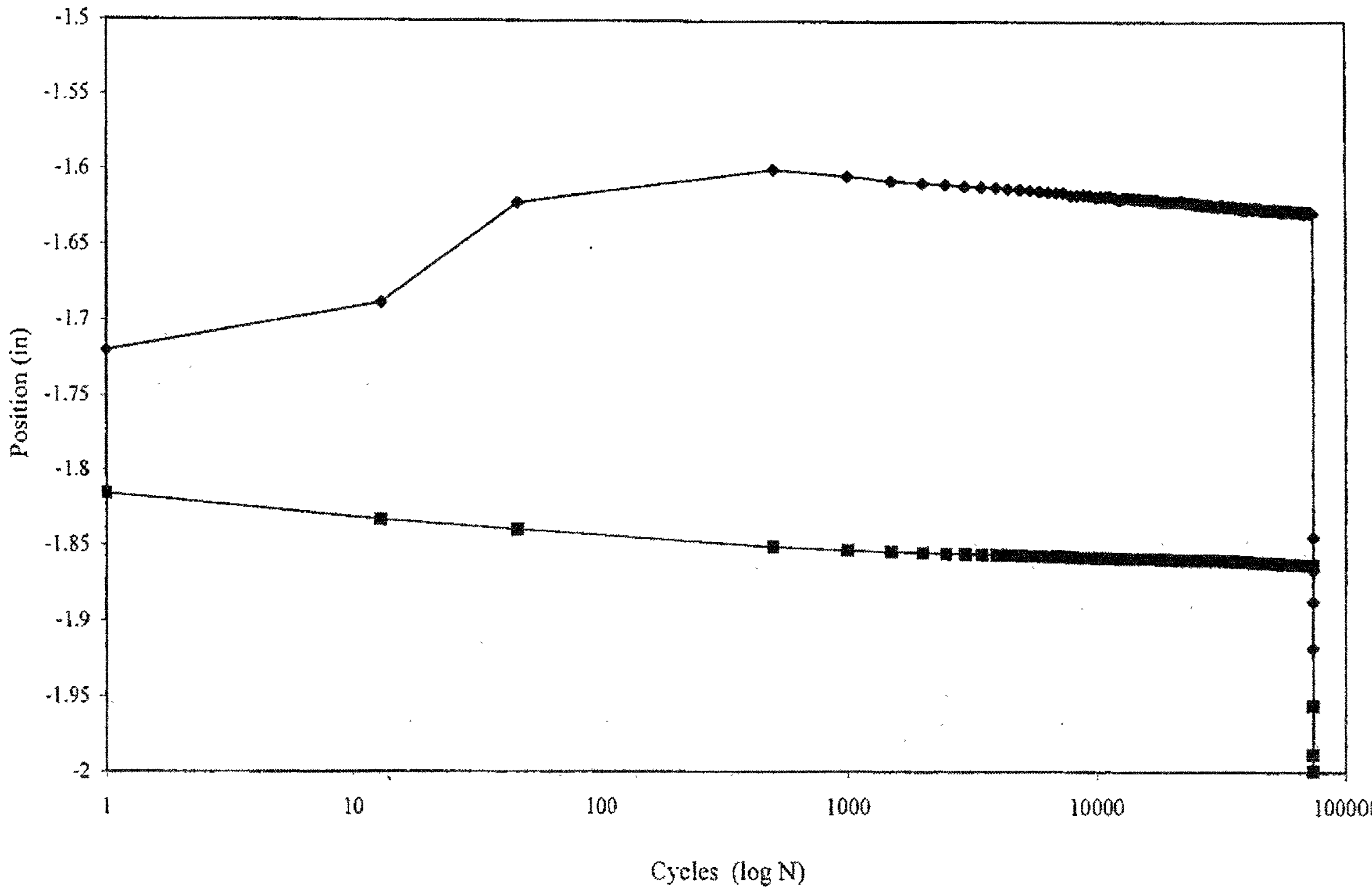

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Figure 3 Cyclic Fatigue Load Dependent Cycles

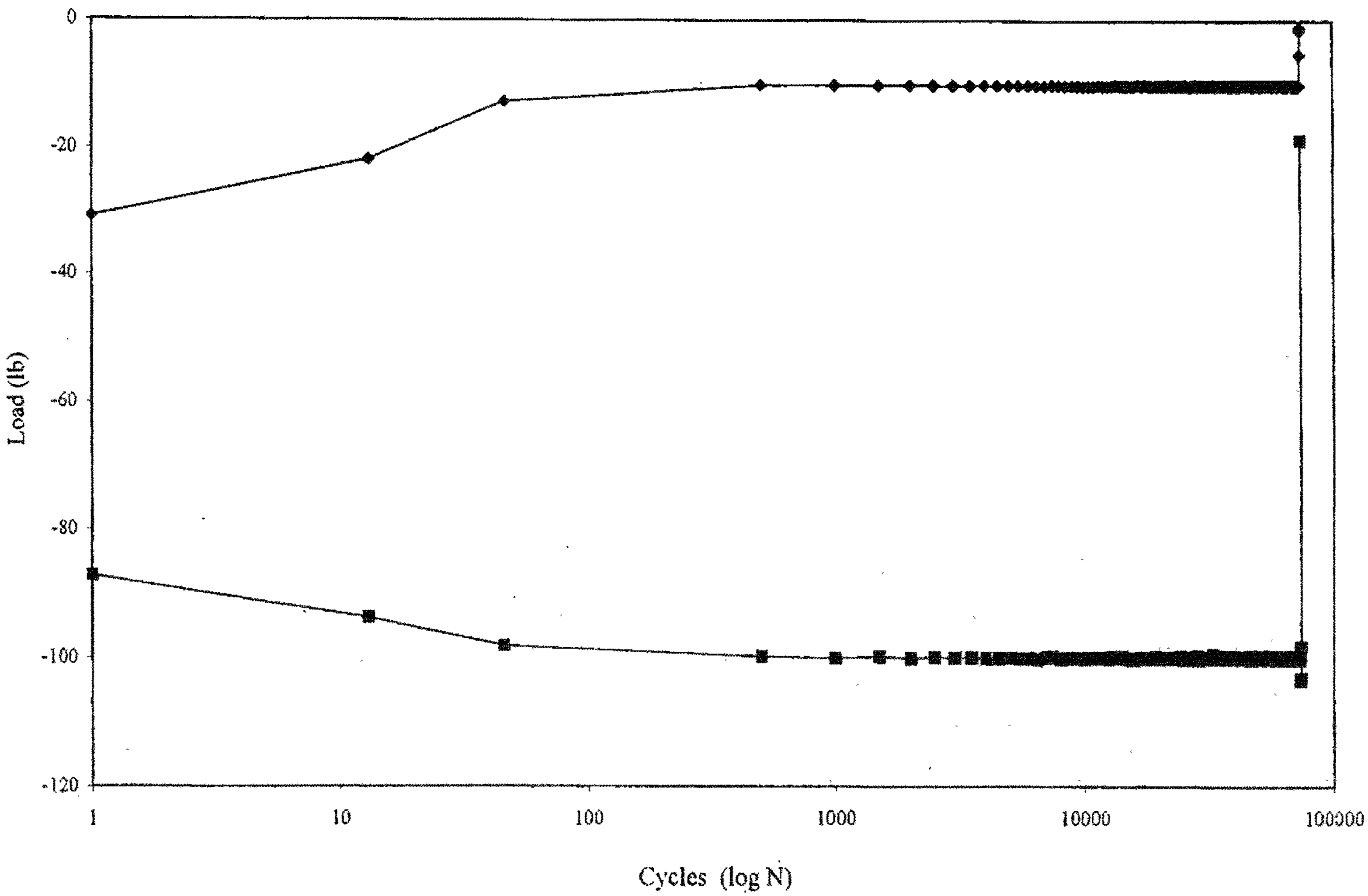

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Figure 4 Cyclic Fatigue Testing of Smooth Round Moderate Profile Gel-Filled Mammary Implants

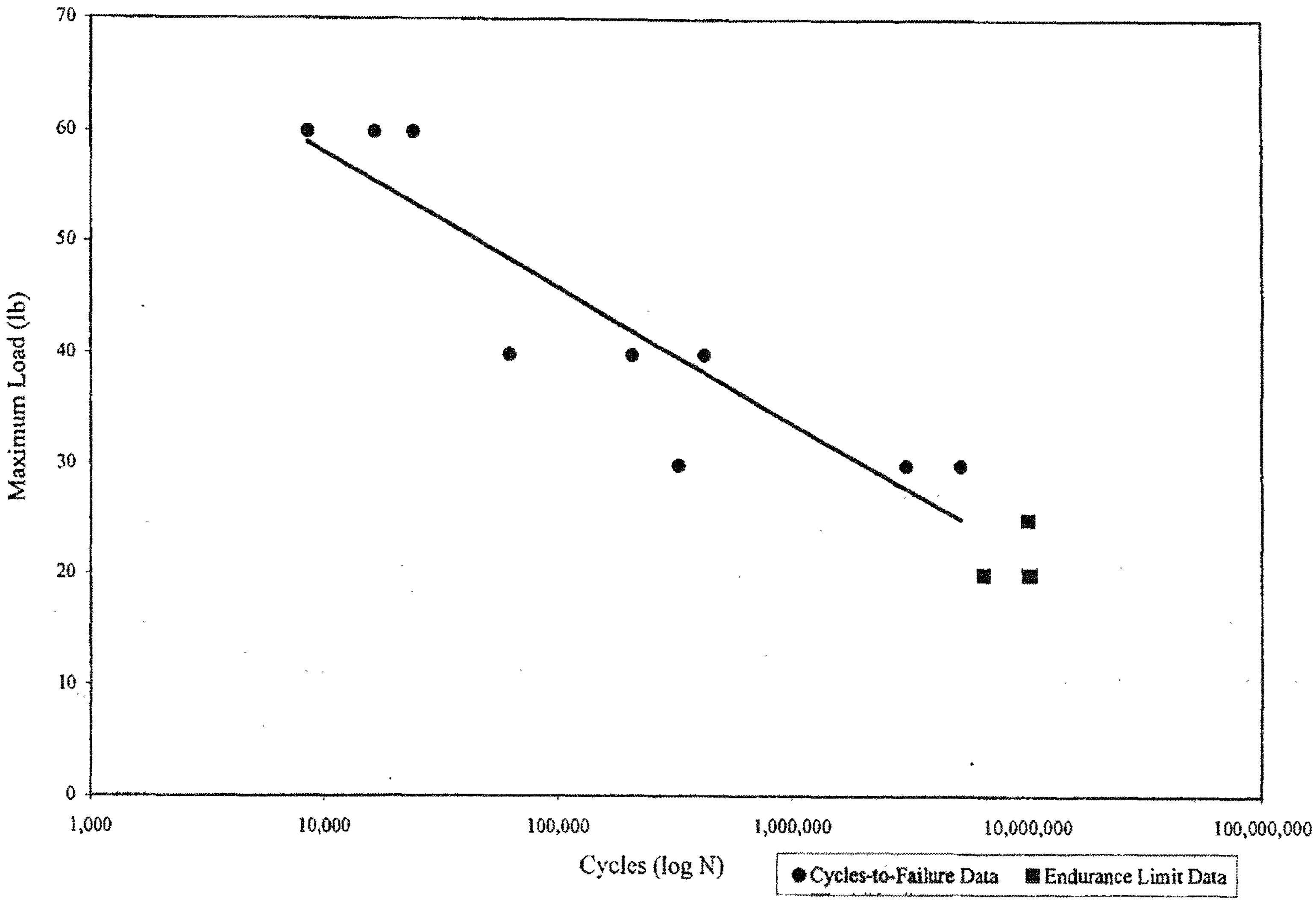

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Figure 5 Cyclic Fatigue Testing of Siltex Round Moderate Profile Gel-Filled Mammary Implants

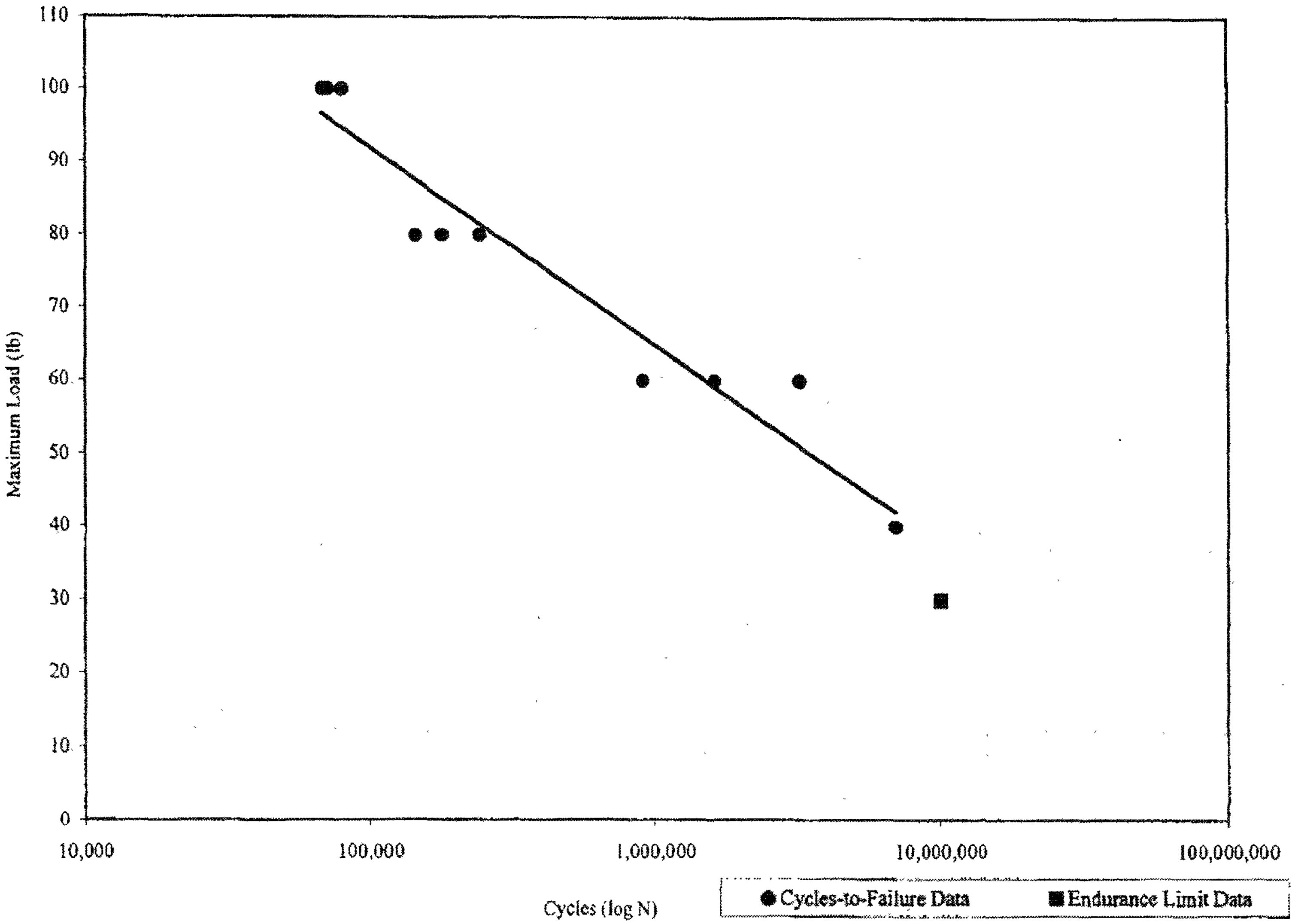

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Figure 6 Cyclic Fatigue Testing of Siltex High Profile Gel-Filled Mammary Implants